environmental
DEFENSE CENTER

May 12, 2021

Jonathan Bishop
John Borkovich
State Water Resources Control Board
1001 I Street
Sacramento, CA 95814

Submitted electronically to Jonathan.Bishop@waterboards.ca.gov and John.Borkovich@waterboards.ca.gov

Re: Expert Report on the Application for Aquifer Exemption in the Sisquoc and Monterey Formations of the Cat Canyon Oil Field, Santa Barbara County Regarding Lack of Evidence to Demonstrate Geologic Confinement and Operational Containment of Injected Fluids

Dear Mr. Bishop and Mr. Borkovich:

The attached expert report is submitted by the Environmental Defense Center ("EDC") on behalf of the Sierra Club, by and through the Los Padres Chapter ("Sierra Club"), Santa Barbara County Action Network ("SBCAN"), and EDC regarding the Application for Aquifer Exemption in the Sisquoc and Monterey Formations of the Cat Canyon Oil Field in Santa Barbara County, California ("Application"). The report prepared by Dr. Bwalya Malama, PhD, identifies significant information gaps and unsupported assumptions in the Application, further evidencing that the Application has not satisfied the criteria under Public Resources Code Section 3131.[1]

Pursuant to the state's criteria for exempting an aquifer, a proposal to exempt an aquifer to inject oil and gas fluids requires the California Geologic Energy Management Division ("CalGEM") and the State Water Resources Control Board ("SWRCB") to ensure, in relevant part, that "[t]he injection of fluids will not affect the quality of water that is, or may reasonably be, used for any beneficial use," and "[t]he injected fluid will remain in the aquifer or portion of

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[1] Dr. Bwalya Malama, PhD, *A Review of the Cat Canyon Aquifer Exemption Expansion Application* (May 12, 2021)(Attachment A); Neuman, S.P., Witherspoon, P.A., 1972. Field determination of the hydraulic properties of leaky multiple aquifer systems. Water Resources Research 8, 1284-1298 (Attachment B); *See also* Dr. Bwalya Malama, PhD, CV (Attachment C).

the aquifer that would be exempted." Pub. Res. Code § 3131(a)(2)-(3). As discussed in detail in the report, neither showing can be made based on the information provided in the Application.

Specifically, the report finds that:

- No data was submitted to "demonstrate that the faults marking the lateral extent of the exempted area are sealed," which is extremely problematic because "faults may serve as conduits for vertical migration of injected fluids;"
- "The vertical extent of the proposed expansion does not sufficiently account for potential leakage from confining units into the overlying formations from which groundwater is extracted;"
- Confining units "are not strictly impermeable," as evidenced by the migration of tar from the Monterey formation into the Upper Sisquoc and Careaga formations;
- Pressure "discontinuities may also be indications of high permeabilities along the fault planes," which was not adequately addressed in the Application and only one fault was analyzed for such discontinuities; and
- "[N]o sufficient rationale is provided in the exemption application for proposing an expansion into the low permeability reaches of the Monterey formation, …."[2]

Dr. Malama holds a PhD in Hydrology, an MS in Geological Engineering, and a BS in Mining Engineering from the University of Arizona. Before joining California Polytechnic State University, he was a senior member of technical staff at Sandia National Laboratories in New Mexico where he investigated groundwater flow and contaminant transport related to geologic disposal of nuclear waste. He also conducted research in innovative methods for characterizing near-surface fluid flow and solute transport systems. Prior to his work at Sandia, he held an Assistant Professor position in Geological Engineering at Montana Tech and a research position at Boise State University. Dr. Malama's research interests are in quantitative (analytical and numerical) modeling of groundwater flow and transport of contaminants in the subsurface, lab- and field-scale investigation of innovative physics-based methods for characterizing flow in the near-surface and very low permeability environments, and development of empirical models for soil moisture.

The Sierra Club is dedicated to exploring, enjoying, and protecting the wild places of the earth; to practicing and promoting the responsible use of the earth's ecosystems and resources; to educating and encouraging humanity to protect and restore the quality of the natural and human environment; and to using all lawful means to carry out these objectives. SBCAN is a countywide grassroots organization that works to promote social and economic justice, to preserve our environmental and agricultural resources, and to create sustainable communities. EDC is a non-profit, public interest law firm that protects and enhances the environment in Santa Barbara, Ventura, and San Luis Obispo Counties through education, advocacy, and legal action.

[2] *Id.*

Our clients have members who live, visit, work, and recreate in the Cat Canyon area and would be affected by the approval of the Application.

Based on the attached reports and the other materials that we have submitted to date, we reiterate our request that the SWRCB not concur on the Application. Thank you for your consideration of this matter. If you have any questions, please do not hesitate to reach out to Tara Messing, EDC Staff Attorney, at 805-963-1622 x104 or TMessing@EnvironmentalDefenseCenter.org.

Sincerely,

LKrop

Linda Krop
Chief Counsel

Tara C. Messing

Tara C. Messing
Staff Attorney

Attachments:
A – Dr. Bwalya Malama, PhD, *A Review of the Cat Canyon Aquifer Exemption Expansion Application* (May 12 2021)
B – Neuman, S.P., Witherspoon, P.A., 1972. Field determination of the hydraulic properties of leaky multiple aquifer systems. Water Resources Research 8, 1284-1298.
C – Dr. Bwalya Malama, PhD, CV

CC:
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Ken Hough, Santa Barbara County Action Network
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Attachment A

A Review of the Cat Canyon Aquifer Exemption Expansion Application

Bwalya Malama, Ph.D.*[1]

[1] *California Polytechnic State University, San Luis Obispo, California*

Background and Scope

This review of the Cat Canyon Aquifer Exemption Expansion Application evaluates whether geologic confinement and operational containment of injected fluids are achievable with the current aquifer exemption expansion boundaries. This is accomplished by a review of the evidence contained in the exemption expansion application for geologic confinement and operational containment under the proposed expanded boundaries. The review is based on publicly available records from the State Water Resources Control Board.

The results of the review indicate that there are currently no data submitted with the exemption application that demonstrate that the faults marking the lateral extent of the exempted area are sealed. Data are included in the application for tests conducted in the vicinity of one fault. However, it is clear that the exemption application does not consider an alternative interpretation of the results of the tests, which suggests that the observed behavior may be attributable to flow along the plane of the fault. A lack of flow across a fault may not be an indication of a sealed fault but of flow along a high permeability pathway in the plane of the fault. Hence, instead of acting an bounds of confinement, faults may serve as conduits for vertical migration of injected fluids. Additionally, no sufficient rationale is provided in the exemption application for proposing an expansion into the low permeability reaches of the Monterey formation, beyond the localized producing fracture zones. The vertical extent of the proposed expansion does not sufficiently account for potential leakage from confining units into the overlying formations from which groundwater is extracted. The potential for leakage from these confining units exists as they are not strictly impermeable. This is clear from the migration of highly viscous fluids (tar) that has occurred over geologic time-scales from the Monterey formation, which is recognized as the source rock across the study area, into the Upper Sisquoc and Careaga formations.

In the following, analyses of geologic confinement and operational containment are presented.

Geologic Confinement

Across the study area and much of Santa Maria petroleum region, the Monterey Formation is recognized as the source rock (Isaacs, 1992). The chert member of the Monterey formation serves as an important reservoir formation in regions with natural fracture. The formation is considered impermeable in areas with no natural fractures. The Upper Sisquoc Member of the Sisquoc (sand/sandstone zones) formation is also an important reservoir formation in Cat Canyon, with crude oil having migrated into it from the underlying Monterey source rock (Woodring and Bramlette, 1950; Isaacs, 1992). Over geologic time, it is indubitable that cross-flow of fluids has occurred from the Monterey source rock into the Sisquoc and Careaga formations (as evidenced by the tar sands of the Careaga formation). The question of interest here is whether operations such as steam injection, water flooding, and waste/produced water disposal in the Monterey formation and the Upper Sisquoc formation, can induce migration of these fluids into overlying groundwater formations. The evidence presented in the application for the expansion of the aquifer exemption for Cat Canyon is reviewed here.

1. **Stratigraphic Separation & Confining Layer Permeabilities**: According to the application for the exemption expansion, geologic confinement is achieved in part by stratigraphic separation or isolation of the near-surface groundwater bearing formations (alluvium, Paso Robles, and Careaga Sandstone) from the Upper Sisquoc and Monterey formations. The near-surface groundwater bearing formations are separated from the Upper Sisquoc formation by the thick and low permeability Foxen

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formation and the Upper Sisquoc Confining unit. The reported average hydraulic conductivities of these two low permeability formations are $K = 1.8 \times 10^{-8}$ m/s (1.6 mm/day) for the Foxen formation, and $K = 1.26 \times 10^{-7}$ m/s (11 mm/day) for the Upper Sisquoc Confining unit.

Whereas it is clear that the average permeabilities of the Foxen formation and the Upper Sisquoc Confining unit are very low, these confining units cannot be said to be strictly impermeable. The stated stratigraphic separation or isolation does not necessarily equate to hydraulic separation. The hypothesis that stratigraphic separation implies hydraulic confinement needs to be tested experimentally at the field scale. One has to demonstrate, through field-scale hydraulic testing, that no cross-flow occurs among the separate stratigraphic units. Cross-flow depends on permeabilities of the stratigraphic units, and the hydraulic gradients across them. The permeability values provided in the exemption expansion application, when compared to values reported in the literature (Neuman and Witherspoon, 1972) for leakage from confining units, indicate that hydraulic separation is not assured. Establishing confinement only on the basis of groundwater well completion depths and the depth to the confining layers (Foxen formation and Upper Confining Layer of Sisquoc Formation) is not sufficient to demonstrate that operations in Upper Sisquoc Formation would have no impact on overlying aquifers. Neuman and Witherspoon (1968, 1972) developed and tested, at the field scale, a model for groundwater leakage, from low pearmeability but high storage confining layers, when a confined aquifer is subjected to groundwater abstraction. The study showed that pumping from an aquifer can induce appreciable and measurable drawdown in the low permeability layers, indicative of fluid leakage from such layers. The hydraulic conductivities of the confining layers reported in that study averaged $K = 1.9 \times 10^{-8}$ m/s (1.6 mm/day), which is comparable to the values for the the Foxen formation and about an order of magnitude less than those of the Upper Sisquoc Confining unit. They were determined from measurements of drawdown in the confining units induced by pumping from the aquifer. The results of the work of Neuman and Witherspoon (1968, 1972) clearly demonstrate, from theory and field-scale hydraulic testing, that stratigraphic separation does not equate to hydraulic confinement. Confining layers can be large stores of groundwater, which slowly leaks into pumped aquifers because these confining layers, when they are clayey, tend to have higher porosities and compressibilities. This leakage from, and across, these low permeability confining units can lead to transport of contaminants from oil and gas operations in the underlying formations.

The vertical extent of the proposed expansion includes Lower Sisquoc Confining Layer. The Lower Sisquoc Confining Layer is not part of the current exemption area. The application argues that this layer is strictly impermeable, and acts to impede fluids injected into the Monterey formation from migrating upwards. It is, therefore, unclear why the application also proposes to expand the exemption area into this member of the Sisquoc formation, the Lower Sisquoc Confining Layer.

Four groundwater (4) wells are reported (pages 91 and 106) to be completed in the Foxen Formation across the study area and two (2) in the Upper Confining Layer of the Sisquoc Formation. This is an indication that the depictions of homogeneous formations in the cross-sectional representations, based on average formation permeabilities, can be misleading. The Foxen formation and the Upper Confining Layer of the Sisquoc Formation are clearly heterogeneous and can be locally permeable, to the extent of yielding water to groundwater wells. Averaged characterizations of these formations as confining and impermeable neglects the preferential flow paths that may exist in these layers, making them heterogeneous and leaky to some degree, and therefore not strictly hydraulically confining. Woodring and Bramlette (1950) indicates that the Foxen formation includes the mudstone, siltstone, and fine-grained sandstone, and that it is missing in some areas of the study area, which can be seen from the cross-sections provided in the exemption expansion application. Woodring and Bramlette (1950) also states that the Foxen formation is generally thick in synclines of the Santa Maria Basin, and thin or absent in anticlines.

According to the material on Page 68 (subsection 4.1.3) of the document reviewed here and discussed in Woodring and Bramlette (1950), tar originating from the Monterey source rock is present in local zones of the Careaga formation. Migration of tar from the Monterey formation into the Careaga Sandstone could be indicative of the ineffectiveness of geologic confinement or stratigraphic separation. Basically, this suggests that, under certain conditions, natural or man-induced, fluids can migrate from the Monterey formation to the overlying Careaga formation through all the intervening low permeability geologic layers. It would be instructive to include, in the Application, a discussion of the natural geologic/historical conditions that induced the migration of fluids (tar) from the Monterey formation source rock into this Careaga Sandstone outcrop.

2. **Monterey Formation Permeability and Fractures**: It is not clear from the exemption expansion application document whether the fracture zones in the Monterey Formation have mapped and what the lateral (east-west and north-south) extent of the fracture zones may be. It is however, presented

in the document that the fracture zones in the Monterey formation are localized, with permeabilities outside these localized fracture zones being comparable to those of the confining units; the Monterey formation is basically impermeable beyond these localized high permeability fracture zones in the Chert Member (Woodring and Bramlette, 1950). This, therefore, raises the question as to why the exemption area in the Monterey formation should be expanded beyond the localized fracture zones into the impermeable zones. It remains unclear as to why there is a need to expand the exemption area into the far reaches of the Monterey formation where it is impossible to inject waste water because of the absence of natural fractures. The inherent contradiction in the argument for expansion of the exemption areas in the Monterey formation beyond the localized naturally fractured zones should be resolved. Production in the Monterey Formation is in localized fractured zones. Therefore, injection of waste water should also be limited to these localized fracture zones.

3. **Sealing Faults**: Faults form boundaries of fault blocks in the expanded exemption area, yet their permeabilities are not specified. The faults may be laterally sealing, but highly permeable in the planes on the faults, acting as conduits for vertical migration of injected fluids. Two types of tests have been performed in the past to demonstrate that one of these faults is sealing or impermeable.

    (a) Dye Tracer Test: The test was used to demonstrate the sealing nature of the fault roughly marking the eastern extent of the existing exempted area. Uranine dye was injected in one well (Priesker #1, perforated in Monterey Formation in interval 1939-3648 ft) and breakthrough behavior monitored in 8 wells. Only one well (Hammon #11, completed in Monterey Formation in interval 1950-4000 ft) was monitored east of the fault and it was the only well not to show dye breakthrough. The dye tracer test results were interpreted to indicate impermeability of the fault. However, there is an alternative hypothesis or interpretation of these results, namely that the fault permeability in the plane of the fault is higher that of the formation such that the injected dye flows along or in the plane of the fault as opposed to flowing across the fault. A fault is a fracture, and fractures in the Monterey formation, as noted in the exemption application, are coextensive with the major faults and are known to be highly permeable; they account for the high permeabilities (or hydraulic conductivities, $K = 8.4 \times 10^{-5}$ (7.3 m/day) to 2.94×10^{-4} m/s (25.4 m/day)) associated with the productive zones of the middle fractured chert member of the Monterey formation. A high permeability fault (within the fault plane) may explain the relatively early dye breakthrough observed in some of the sampling locations (see wells Hammon #9, #10, and #13 in Appendix 6-III, Proof of Confinement, of application) along the fault on the south to southwestern side of the fault.

    Dye tracer test results also demonstrate the spread of injected fluids away from the points on injection. The dye was detected hundreds to a few thousands of feet away from the injection well over a relatively short period five days.

    The statistical significance of the non-detect result for well Hammon #11 (Appendix 6-III) is debatable. A properly designed field test of the sealed nature of the fault using a dye tracer would have a good representative sample of sampling wells on the other side of the fault too.

    Additionally, a dye tracer test has only been performed in the neighborhood of one fault. In this review, no data were found of dye tracer tests in the neighborhood of other "sealing" faults. Given the importance of such data in determining extent of the current exemption zones, it is recommended that dye tracer tests be conducted around the Garey Fault and the unnamed fault that marks the major eastern or northeastern extent of the proposed expanded exemption area. Basically, it would be advisable to perform dye tests in the neighborhood of all faults that are hypothesized to be sealing faults and a used as justification for the expanded aquifer exemption application. The faults, as stated above, may be laterally sealing but highly permeable in the fault plane. They may act as conduits for vertical migration of injected fluids by providing high permeability preferential flow paths from deep formations into overlying freshwater aquifer.

    Faults can become unsealed by high-pressure and high-temperature fluid injection, leading to fault slip and induced seismicity (Kim, 2013; Guglielmi et al., 2015; Doglioni, 2018). The mechanism of fault sealing may be accumulation of high-viscosity crude oil, that would be mobilized by high-temperature fluid injection. Additionally, fluid pressures may introduce high pore pressures along fault planes, which can lead to fault lubrication and mobilization (Doglioni, 2018). Fault slip and migration of highly viscous fluids from the fault plane can lead to greater vertical spreading of injected fluids.

    (b) Pressure Discontinuities: Pressure discontinuities or differentials across faults are also interpreted to be evidence of the sealing nature of faults across which they are observed. However, such discontinuities may also be indications of high permeabilities along the fault planes. They may be indications of fluid flow into and along the dip/planes of the faults. Whereas flow along the plane of the faults may impede lateral spreading of injected fluids, it may enhance their vertical migration.

Before the state should decide to expand the exemption area, it is recommended that there should be a requirement for field testing of the integrity of seal of the faults of the proposed fault blocks. Only one fault has been investigated with a dye tracer test, and only one fault is analyzed for pressure discontinuity across the fault. Data that demonstrates that the faults are sealed would be very useful in determining whether geologic and operational confinement are achievable with the proposed boundaries or with a reduced exemption area.

Operational Containment

Pressure field around production zones are argued to be favorable to containment of fluids. However, only limited consideration is given to injection zones, where pressure gradients are such that fluids would naturally flow away from. Injected fluids have a tendency to diverge and migrate away from injection zones. It would be instructive to plot pressure contours and fluid flow vectors in the neighborhood of injections wells. Emphasis is placed on the low pressure fields associated with production areas but not with the high pressure fields generated around injection areas. Whereas there is a tendency for fluids to flow toward production areas, there is also a tendency for fluids to flow away from injection areas. The latter, migration of fluids from injection zones beyond the capture by production zones, is of greater concern in assessing potential for fluid migration from injection areas. Whereas hydraulic gradients may be inward and favorable to confinement in production zones, they are outwardly directed from injection zones and counteract the effect of production.

Concluding Remarks

The evidence presented in the application for the expansion of the aquifer exemption for the Cat Canyon field, namely favorable subsurface stratigraphy and pressure gradients in the producing formations, suggests that there is a need to empirically test some of the inherent assumptions. It is assumed that the low permeabilities of the strata that separate near-surface groundwater resources from producing and injection reservoirs are sufficient to prevent migration of injected fluids beyond the exemption bounds. It is also assumed, based on limited testing near a single fault, that all faults across the study area are sealing. Additionally, no analysis of pressure fields around injection wells is presented. The application considers pressure field data only around production zones. This is not sufficient to demonstrate that fluid migration from injection wells cannot extend beyond the bounds of the exemption area. A dye tracer test cited in the application appears to demonstrate wide spread, on the order of a mile, of the fluids injected in a Monterey formation well.

It is of interest that not attempt is made in the application document reviewed here to present evidence of how well the subsurface has performed under the current exemption bounds. There should be metrics to assess the performance of geologic confinement and operational containment, which would demonstrate that under the current aquifer exemptions, no fluids injected in these reservoirs have migrated beyond current bounds. It is not clear whether it is even possible to assess the performance of geologic and operational containment of current exemption. Such an assessment would serve to answer such questions as

1. Has the subsurface system performed as it should have under the current exemption?
2. Have the injected fluids not affected the quality of water that is, or may reasonably be, used for beneficial use and remain[ed] in the aquifer or portion of the [exempted] aquifer?
3. How do we know this and to what extent have the results of such an assessment informed the decision making process on exemption expansion application?

If such an assessment tool exists, and performance assessment has been carried out for the present case, the general findings should at least be included in this application.

The results of the review indicate that there are currently no data submitted with the exemption application that demonstrate that the faults marking the lateral extent of the exempted area are sealed. Data are included in the application for tests conducted in the vicinity of only one fault. The results of tests on one fault cannot be used to infer the behavior of all the faults across the study area. It is also clear that the exemption application does not consider alternative interpretations of the results of the tests. The results may be interpreted to indicate that the observed behavior is attributable to flow along the plane of the fault. A lack of flow across a fault may not be an indication of a sealed fault but of flow along a high permeability pathway in the plane of the fault. Hence, instead of acting as bounds of confinement, faults may serve as conduits for rapid vertical migration of injected fluids.

Additionally, no sufficient rationale is provided in the exemption application for proposing an expansion into the low permeability reaches of the Monterey formation, beyond the localized producing fracture zones. The vertical extent of the proposed expansion does not sufficiently account for potential leakage from confining units into the overlying formations from which groundwater is extracted. The potential for leakage from these confining units exists because these layers are not strictly impermeable. Migration of highly viscous fluids (tar) has occurred over geologic time-scales from the Monterey formation, which is recognized as the source rock across the study area, into the Upper Sisquoc and Careaga formations as reported in Woodring and Bramlette (1950).

References

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Neuman, S.P., Witherspoon, P.A., 1972. Field determination of the hydraulic properties of leaky multiple aquifer systems. Water Resources Research 8, 1284–1298.

Woodring, W.P., Bramlette, M.N., 1950. Geology and paleontology of the Santa Maria district, California. Technical Report. US Geological Survey.

Other Minor Comments

The following are some additional comments and questions:

1. Page 11: Under Agricultural Wells, what is meant by the statement "demonstrates adequate confinement"? It implies hydraulic testing has been performed at the field-scale to ***demonstrate*** absence of leakage. The aquitard/aquifer interface could be leaky.
2. Page 16: Groundwater barriers are defined on the basis of a literature search instead of *site-specific* hydraulic aquifer testing.
3. Page 17: Confinement is defined on the basis of water well completion depths relative to the depth to the confining units. This is a stratigraphic confinement, not a hydraulic confinement in the case of leaky aquifer-aquitard systems.
4. Figures 3.2-3a,b (Cross-section BB'): The contact or interface between the Upper Sisquoc Confining Layer and the Upper Sisquoc is shown as uncertain. This needs to be expounded upon with maybe a brief statement of the degree of uncertainty associated with the depth to this interface. This may have implications on the thickness of the Upper Sisquoc Confining Layer. The same can be said of the base of the Monterey formation.
5. Figure 3.2-5aa (Cross-section DD'): The extrapolation of the pinchout of the Foxen formation needs to be explained a bit more. It thins and is missing in some parts leaving the Careaga Formation to sit in direct contact with the Upper Sisquoc Confining Layer. It is not clear why it is extrapolated as far to the southeast as it is.
6. Page 49 (last paragraph): It states here that steam and water for injection are *typically* sourced from produced water. This suggests that there are additional sources of water, presumably groundwater from overlying aquifers. It is important to quantify this additional water and to account for it in the material/fluid balance computations and analysis.
7. Note here that the permeability of the Monterey Chert zone is reported on page 69 (section 4.1.6 Monterey Formation) as 10^{-15} darcy. This appears to be a typo.

8. Figure 5.1-15 (Unconfined Groundwater Gradient Map): There is no legend (color bar) for the gradient heat map. It is not clear whether the heat map represents groundwater hydraulic head, and if so, which colors correspond to high or low hydraulic head. Hence, the reader cannot independently evaluate the direction of unconfined groundwater flow in the study area.
9. Instead of comparing the TDS and Boron concentrations of groundwater in Alluvium, Paso Robles, and Careaga formations to those of the Upper Sisquoc and Monterey Formations, it would be more instructive to compare the Boron isotopic compositions. The former only establishes the already known fact that the two waters are different. The latter would allow one to establish whether there is mixing occurring.
10. Time-scales of geologic isolation need to be specified by the state. For example, for the case on nuclear waste disposal, Yucca Mountain time-scale is 1 million years, and WIPP (Carlsbad, NM) is 10,000 years. How long are injected fluid supposed to remain in the exempted area/zone? At geologic time-scales, fluids are expected to migrate even in the ultra-low permeability units.

Attachment B

Field Determination of the Hydraulic Properties of Leaky Multiple Aquifer Systems

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Abstract. A new field method is proposed for determining the hydraulic properties of aquifers and aquitards in leaky systems. Conventional methods of analyzing leaky aquifers usually rely on drawdown data from the pumped aquifer alone. Such an approach is not sufficient to characterize a leaky system; our new method requires observation wells to be placed not only in the aquifer being pumped but also in the confining layers (aquitards) above and/or below. The ratio of the drawdown in the aquitard to that measured in the aquifer at the same time and the same radial distance from the pumping well can be used to evaluate the hydraulic properties of the aquitard. The new method is supported by theory and has been applied to the coastal groundwater basin of Oxnard, California. The field results are in good agreement with laboratory measurements.

Traditionally, groundwater hydrologists have tended to focus their attention on the more permeable aquifer layers of a groundwater basin in developing water supplies. However, sedimentary groundwater basins usually consist of a series of aquifers separated by confining layers of relatively low permeability, which may act as conduits for the vertical migration of water from one aquifer to another. Since fine-grained sediments often tend to be much more compressible than associated coarse-grained aquifer materials, they also can release large quantities of water from storage and thereby increase the supply available to the aquifer. The combined effects of these phenomena are known as leakage.

Usually, when the effects of leakage can be detected by observing drawdown in the aquifer being pumped, the confining beds are called 'aquitards,' and the aquifer is referred to as being 'leaky.' When such effects cannot be easily detected in the aquifer, the confining beds are called 'aquicludes,' and the aquifer is termed 'slightly leaky' [*Neuman and Witherspoon*, 1968].

Aquitards play an important role in the hydrology of multiple aquifer systems, and we shall mention here only a few examples. Although groundwater recharge is often believed to occur in areas of aquifer outcrops, *Gill* [1969] has recently reported that substantial amounts of water produced from the Potomac-Raritan-Magothy aquifer system are coming through the aquitards. Earlier, *Walton* [1965] had shown how the Maquoketa formation in Illinois, which is essentially a shale bed, serves as an effective transmitter of water between aquifers. Land subsidence in the San Joaquin Valley and other areas in California has been shown to be associated with water withdrawal from multiple aquifer systems and is generally attributed to the resulting compaction of fine-grained aquitard sediments [*Poland and Davis*, 1969]. Similar situations exist in Venice, Japan, and other parts of the world.

For the past 20 years, aquifers at depths below 500 feet have been used for storing natural gas in the United States and Europe. Where the properties of the aquitards were not properly investigated, the gas industry has on occasion witnessed the spectacular and dangerous effects of gas leakage. The storage of other fluids, as well as the disposal of waste products underground, requires the role of aquitards to be thoroughly understood if the degradation of groundwater supplies and the pollution of the surface environment are to be avoided. The role of aquitards may also be important in determining the rate at which the seawater from a degraded aquifer may migrate vertically to an uninvaded zone. An interesting situation in which the effectiveness of aquitards in preventing seawater intrusion is largely unknown occurs where the construction of shallow harbors and marinas requires the removal of a part of the aquitard that normally provides a natural barrier between the ocean and the freshwater aquifer beneath [*California Department of Water Resources*, 1971, p. 10].

Although the importance of aquitards is being recognized more and more, there is no reliable method for their investigation, and very little is known about their hydraulic properties. This report describes an improved field method for evaluating the hydraulic properties of aquifers and aquitards in leaky multiple aquifer systems. The new approach is simple to use and applicable to a wide range of hydrogeological situations. We shall describe in detail one particular investigation performed in the coastal groundwater basin of Oxnard, California.

PROBLEMS IN ANALYZING PUMPING TESTS WITH CURRENT METHODS

In analyzing results of water pumping tests the well-known *Theis* [1935] solution is often used to determine the permeability and the specific storage of the aquifer under investigation. As long as the aquitards do not leak significant amounts of water into the aquifer, this method of analysis produces reliable results.

However, groundwater hydrologists noted many years ago that deviations from the aquifer behavior, as predicted by the Theis solution, are not uncommon. These deviations are often caused by water leaking out of the confining beds, and this led to the 'leaky aquifer' theory of *Hantush and Jacob* [1955]. This theory and its later modifications [*Hantush*, 1960] relied only on an examination of aquifer behavior and attempted to relate such behavior to the properties of the adjacent aquitards.

Unfortunately, this approach has not been entirely satisfactory. As has recently been pointed out by *Neuman and Witherspoon* [1969*b*], field methods based on the leaky aquifer theory of *Hantush and Jacob* [1955] may often lead to significant errors. These errors are such that one tends to overestimate the permeability of the aquifer and underestimate the permeability of the confining beds. Under some circumstances, one may also get the false impression that the aquifer is inhomogeneous. Furthermore, the method does not provide a means of distinguishing whether the leaking beds lie above or below the aquifer being pumped.

A new theory of flow in multiple aquifer systems has recently been developed by *Neuman and Witherspoon* [1969*a*; *California Department of Water Resources*, 1971, pp. 24–38]. This theory shows that the behavior of drawdown in each layer is a function of several dimensionless parameters β_{ij} and r/B_{ij}, which depend on the hydraulic characteristics of the aquitards as well as those of the aquifers. The new theory clearly indicates that the observation of drawdown in the pumped aquifer alone is not always sufficient to determine uniquely the values of β and r/B. For example, *Hantush*'s [1960] modified theory of leaky aquifers provides an analytical solution in terms of β that we know is applicable at sufficiently small values of time. Nevertheless, since this solution relates only to drawdown in the aquifer being pumped, its usefulness in determining uniquely the properties of each aquitard or even in determining a unique value of β is very limited [*California Department of Water Resources*, 1971, p. 327; *Riley and McClelland*, 1970]. Our theory indicates that one should be able to develop improved methods of analysis by installing observation wells not only in the aquifer being pumped but also in the confining layers enclosing it. Indeed, as will be shown later, a series of observation wells in more than one layer is a prerequisite for any reliable evaluation of aquitard characteristics.

The idea of placing observation wells in a low permeability layer (aquiclude) overlying a slightly leaky aquifer was originally proposed by *Witherspoon et al.* [1962] in connection with the underground storage of natural gas in aquifers. Their purpose was to determine how effective a given aquiclude would be in preventing gas leakage from the intended underground storage reservoir. Using results obtained from a finite difference simulation model, Witherspoon et al. were able to suggest a method for evaluating the hydraulic diffusivity of an aquiclude by means of a pumping test.

Later, a theoretical analysis of flow in aquicludes adjacent to slightly leaky aquifers was developed by *Neuman and Witherspoon* [1968]. This theory led to an improved method for determining the hydraulic diffusivity of aquicludes under slightly leaky conditions [*Witherspoon and Neuman*, 1967; *Witherspoon et al.*, 1967, pp. 72–92]. Since the method relies on the ratio between drawdown in the aquiclude and drawdown in the pumped aquifer, it will henceforth be referred to as the 'ratio method.'

A method for evaluating the hydraulic diffusivity of an aquitard under arbitrary conditions of leakage, which also uses observation wells completed in the confining layer itself, was recently described by *Wolff* [1970]. In his analysis Wolff assumed that, at any given radial distance from the pumping well and at a sufficiently large value of time, one can represent drawdown in the pumped aquifer by a step function. Assuming also that drawdown in the unpumped aquifer remains 0, Wolff arrived at a set of type curves that he recommended for aquitard evaluation.

Although this method gave satisfactory results for the particular site investigated by Wolff, we think that the step function approach may lead to difficulties when it is applied to arbitrary multiple aquifer systems. Fundamentally, drawdown in the pumped aquifer cannot be reliably represented by a single step function unless a quasi-steady state is reached within a sufficiently short period of time. The quasi-steady state will be reached only if the transmissibility of the aquifer is large and if the observation wells are situated at relatively small radial distances from the pumping well. To minimize the effect of early drawdowns, Wolff's method further requires that the duration of the pumping test be sufficiently long and that the vertical distance between the pumped aquifer and the aquitard observation wells not be too small.

From our new theory of flow in multiple aquifer systems, we now know that at large values of time the results in the aquitard may be affected significantly by the influence of an adjacent unpumped aquifer, especially where the aquitard observation well has been perforated close to such an aquifer. Thus, although the single step function approach renders the method inapplicable at small values of time, the assumption of zero drawdown in the unpumped aquifer introduces an additional restriction at large values of time.

In the special case where the thickness of the aquitard is known, one can determine its diffusivity directly from the step function type curves without the need for graphical curve matching. Quite often, however, the effective thickness of the aquitard is unknown. For example, the aquitard may contain unidentified or poorly defined layers of highly permeable material that act as a buffer to the pressure transient and also as a source of leakage. Another possibility is that the aquitard is situated below the pumped aquifer and that its lower limit has never been adequately defined. Then the step function approach requires the graphical matching of aquitard drawdown data with *Wolff*'s [1970] type curves.

However, the intermediate parts of these type curves are essentially parallel, and therefore they cannot be matched uniquely with field results. On the other hand, neither the early nor the late parts of the type curves can be used with confidence. Thus there may be a significant element of uncertainty when *Wolff*'s [1970] method is applied to real field situations.

Since the currently available direct field methods appear to be limited in their application, there is an obvious need for a new approach that would enable one to determine the characteristics of multiple aquifer systems under a wide variety of field conditions. We shall attempt to demonstrate that a rational basis for such an approach is provided by our new theory of flow in multiple aquifer systems [*Neuman and Witherspoon*, 1969a]. We will start by showing that the ratio method, which we originally thought was limited in application only to aquicludes under slightly leaky conditions, can in fact also be used to evaluate the properties of aquitards under very leaky conditions.

APPLICABILITY OF THE RATIO METHOD TO LEAKY CONDITIONS

To develop a method for determining the hydraulic properties of aquitards, we shall first consider a two-aquifer system (Figure 1). A complete solution for the distribution of drawdown in such a system has been developed by *Neuman and Witherspoon* [1969*a*]. In each aquifer the solutions depend on five dimensionless parameters β_{11}, r/B_{11}, β_{21}, r/B_{21}, and t_{D_1}. In the aquitard the solution involves one additional parameter z/b_1'. This large number of dimensionless parameters makes it practically impossible to construct a sufficient number of type curves to cover the entire range of values necessary for field application. For a set of type curves to be useful, they are normally expressed in terms of not more than two independent dimensionless parameters.

One way to significantly reduce the number of parameters is to restrict the analysis of field data to small values of time. In particular, we want to focus our attention on those early effects that occur prior to the time when a discernible pressure transient reaches the unpumped aquifer. At such early times the unpumped aquifer does not exert any influence on the rest of the system, and therefore drawdowns are independent of the parameters β_{21} and r/B_{21}. Furthermore, the aquitard behaves as if its thickness were infinite, which simply means that the parameters r/B_{11} and z/b_1' also have no influence on the drawdown. Thus the resulting equation will depend only on β_{11}, t_{D_1}, and an additional parameter t_{D_1}'.

In the pumped aquifer, drawdown is then given by *Hantush*'s [1960] asymptotic equation [*Neuman and Witherspoon*, 1969*a*].

$$s_1(r, t) = \frac{Q_1}{4\pi t_1} \int_{1/4t_{D_1}}^{\infty} \frac{e^{-y}}{y} \cdot \operatorname{erfc}\left(\frac{\beta_{11}}{[y(4t_{D_1}y - 1)]^{1/2}}\right) dy \qquad (1)$$

In the aquitard the solution is

$$s_1'(r, z, t) = \frac{Q_1}{4\pi T_1} \int_{1/4t_{D_1}}^{\infty} \frac{e^{-y}}{y} \cdot \operatorname{erfc}\left(\frac{\beta_{11} + y(t_{D_1}/t_{D_1}')^{1/2}}{[y(4t_{D_1}y - 1)]^{1/2}}\right) dy \qquad (2)$$

Theoretically, (1) and (2) are limited to those small values of time that satisfy the criterion

$$t_{D_1} \leq 1.6\beta_{11}^{\,2}/(r/B_{11})^4 \qquad (3)$$

In terms of real time this criterion may also be

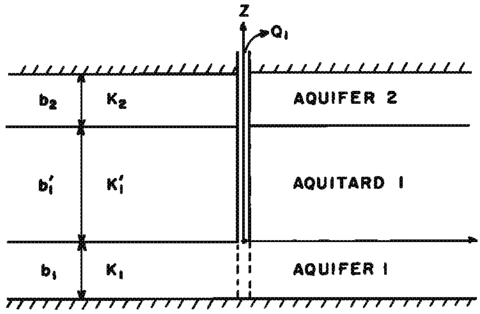

Fig. 1. A schematic diagram of a two-aquifer system.

expressed by

$$t \leq 0.1 S_{s_1}' b_1'^2 / K_1' \qquad (4)$$

indicating that the limiting value of time is independent of the radial distance from the pumping well.

From a practical standpoint the criterion given by (3) or (4) is overly conservative. For example, Figures 2–8 in *Neuman and Witherspoon* [1969*a*] reveal that the effect of the unpumped aquifer is felt in the rest of the system at times that are always greater than those predicted by (3). Note further that in these figures the effects of β_{21} and r/B_{21} are negligible as long as the log-log curve of drawdown versus time for the unpumped aquifer does not depart from its initial steep slope.

This effect of the unpumped aquifer provides a useful criterion for determining the time limit beyond which the asymptotic solutions may no longer be applicable. If an observation well can be provided in the unpumped aquifer, a log-log plot of drawdown versus time should enable the hydrologist to identify this time limit.

Note that there may be field situations in which the procedure above is not applicable. For example, when the transmissibility of the unpumped aquifer is large in comparison to that of the aquifer being pumped, drawdowns in the unpumped aquifer will be too small to measure, and one would not be able to determine the time limit as outlined above. This procedure may also fail when the water levels in the unpumped aquifer are fluctuating during the pumping test owing to some uncontrolled local or regional effect. Then a more conservative estimate of the time limit can be established from drawdown data observed in one of the aquitard wells. In general, the smaller the vertical distance between the perforated interval in the aquitard well and the boundary of the pumped aquifer is, the more conservative the time indicated by the procedure above is.

Having established a practical method for estimating the time within which (1) and (2) are valid, we can now proceed to show how these equations lead to the ratio method for evaluating aquitards. Remember that Hantush's equation does not by itself lead to a reliable method for determining a unique value of β_{11} from field results. The same can be said of (2), because it involves three independent parameters β_{11}, t_{D_1}, and t_{D_1}'. However, the usefulness of these two equations becomes immediately evident when one considers s_1'/s_1, i.e., the ratio of drawdown in the aquitard to that in the pumped aquifer at the same elapsed time and the same radial distance from the pumping well.

In the discussion that follows we shall be dealing with only one aquifer and one aquitard, and for the sake of simplicity we shall omit all subscripts. Figure 2 shows the variation of s'/s versus t_D' for a practical range of t_D and β values. Note that at $t_D = 0.2$ changing the value of β from 0.01 to 1.0 has practically no effect on the ratio s'/s. The same is true as t_D increases, and this relationship is shown by the additional results for $t_D = 10^4$.

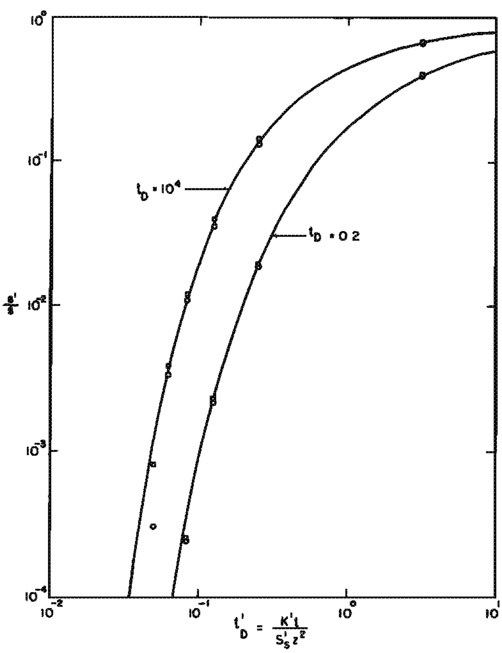

Fig. 2. The variation of s'/s with t_D' for $\beta = 0.0$ (solid lines), $\beta = 0.01$ (squares), and $\beta = 1.0$ (circles).

If we now use our theory for slightly leaky situations [*Neuman and Witherspoon,* 1968] where s' is given by

$$s'(r, z, t) = \frac{Q}{4\pi T}\frac{2}{\pi^{1/2}} \cdot \int_{1/(4t_D')^{1/2}}^{\infty} - \mathrm{Ei}\left(-\frac{t_D' y^2}{t_D(4t_D' y^2 - 1)}\right) e^{-y^2}\, dy \tag{5}$$

and s is obtained from the Theis solution, we have in effect the special case where $\beta = 0$. This is represented by the two solid lines in Figure 2.

We also examined the case where $\beta = 10.0$ and found that the values of s'/s deviate significantly from those shown in Figure 2. Thus one may conclude that for all practical values of t_D the ratio s'/s is independent of β as long as β is of order 1.0 or less. Since β is directly proportional to the radial distance from the pumping well, its magnitude can be kept within any prescribed bounds simply by placing the observation wells close enough to the pumping well. A quick calculation will show that distances of the order of a few hundred feet will be satisfactory for most field situations.

Thus we arrive at the very important conclusion that the ratio method, which we originally thought was restricted to only slightly leaky situations, can in effect be used to determine the hydraulic diffusivities of aquitards under arbitrary leaky conditions. We therefore decided to adopt the ratio method as a standard tool for evaluating the properties of aquitards.

USE OF THE RATIO METHOD IN AQUITARD EVALUATION

The ratio method can be applied to any aquifer and its adjacent aquitards, above and below, in a multiple aquifer system (see sketch in Figure 3). The method relies on a family of curves of s'/s versus t_D', each curve corresponding to a different value of t_D as obtained from (5) and the Theis equation. The curves in Figure 3 have been prepared from tables of values published previously by *Witherspoon et al.* [1967, Appendix G].

In the ratio method, one first calculates the value of s'/s at a given radial distance from the pumping well r and at a given instant of time t. The next step is to determine the magnitude of t_D for the particular values of r and t at which s'/s has been measured. When $t_D < 100$, the curves in Figure 3 are sensitive to minor changes in the magnitude of this parameter, and therefore a good estimate of t_D is desirable. When $t_D > 100$, these curves are so close to each other that they can be assumed to be practically independent of t_D. Then even a crude estimate of t_D will be sufficient for the ratio method to yield satisfactory results. A procedure for determining the value of t_D from drawdown data in the aquifer will be discussed later in connection with methods dealing with aquifer characteristics.

Having determined which one of the curves in Figure 3 should be used in a given calculation, one can now read off a value of t_D' corresponding to the computed ratio of s'/s. Finally, the diffusivity of the aquitard is determined from the simple formula

$$\alpha' = (z^2/t)t_D' \qquad (6)$$

Note in Figure 3 that, when $s'/s < 0.1$, the value of t_D' obtained by the ratio method is not very sensitive to the magnitude of s'/s. As a result the value of α' calculated from (6) depends very little on the actual magnitude of the drawdown in the aquitard. Instead, the critical quantity determining the value of α' at a given elevation z is the time lag t between the start of the test and the time when the aquitard observation well begins to respond. The time lag is very important because in using the ratio method one need not worry about having extremely sensitive measurements of drawdown in the aquitard observation wells. A conventional piezometer with a standing water column will usually give sufficiently accurate information for most field situations. The time lag between a change in pressure and the corresponding change in water level in the column is usually so small in comparison to the time lag between the start of the test and this change in pressure that its influence can be safely ignored.

To evaluate the permeability and specific storage of an aquitard from its hydraulic diffusivity, one of these quantities must first be determined by means other than the ratio method. Experience indicates that permeability may vary by several orders of magnitude from one aquitard to another and even from one elevation to another in the same aquitard. A much more stable range of values is usually encountered when one is dealing with specific storage.

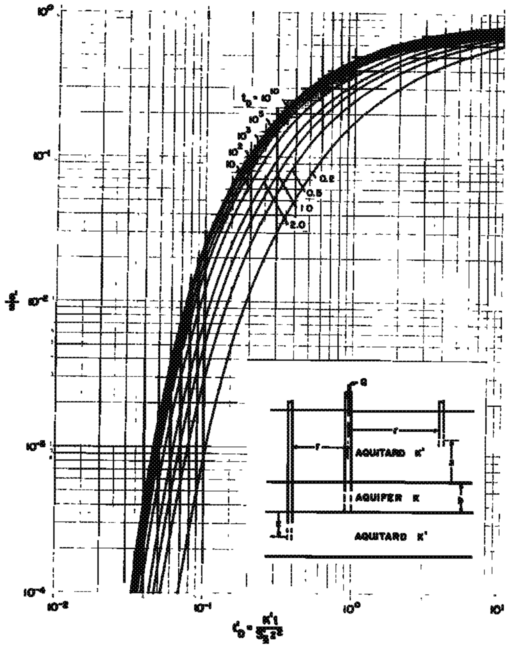

Fig. 3. The variation of s'/s with t_D' for a semi-infinite aquitard.

Recent field measurements in areas of land subsidence (F. S. Riley, personal communication, 1971) have shown that the specific storage of fine-grained sediments depends on the relationship between the load generated by pumping and the past history of loading. When this relationship is such that the sediments react elastically, the value of S_s' is relatively small. When the sediments are undergoing irreversible consolidation, the value of S_s' may be larger by 1 or 2 orders of magnitude. Presently, the most reliable measurements of S_s' are performed in the field by using borehole extensometers. Another way to determine approximate values of S_s' is to perform standard consolidation tests on core samples in the laboratory. In the total absence of field and laboratory measurements, S_s' can be estimated by correlating published results on similar sediments. Once the value of

S_s' has been determined, K' is easily calculated from $K' = \alpha' S_s'$.

We also studied the effects of aquitard heterogeneity and anisotropy on the value of K' obtained by the ratio method at a given elevation a. In our investigation we used the finite element method to examine the behavior of a two-aquifer system when: (1) the aquitard was a homogeneous anisotropic layer with a horizontal permeability as much as 250 times greater than the vertical and (2) the aquitard consisted of three different layers, each of which was homogeneous and anisotropic. The results of this study indicated that for homogeneous anisotropic aquitards the ratio method will always give a value of K' that corresponds to the vertical permeability of the aquitard. For a heterogeneous aquitard, K' is simply the weighted average vertical permeability over the thickness z. If there are N layers of thickness b^n and vertical permeability K_v^n inside this interval, K' represents the average value

$$K' = z \Big/ \left(\sum_{n=1}^{N} \frac{b^n}{K_v^n} \right) \tag{7}$$

Boulton [1963] and *Neuman* [1972] have shown that, at early values of time, drawdown in an unconfined aquifer can safely be approximated by the Theis solution. At later values of time, drawdown is affected by the delayed response of the water table, and the effect is similar to that of leakage in a confined aquifer. Thus, if the ratio method is applicable to aquitards adjacent to confined leaky aquifers, it should also be applicable to situations in which the pumped aquifer is unconfined. This conclusion is further supported by the fact that the ratio method depends less on the actual values of drawdown in the aquifer than on the time lag observed in the aquitard. To test this applicability of the ratio method to an unconfined aquifer, we took data from *Wolff* [1970] for a pumping test in which observation wells were placed in a confining layer underneath a water table aquifer. We analyzed these data by using the ratio method, and the results are in excellent agreement with those obtained by Wolff.

When we showed that our slightly leaky theory was applicable to the so-called leaky aquifer, our previous discussion was restricted to a two-aquifer system. By now, however, the reader will recognize that such a restriction is not necessary and that the ratio method is actually applicable to arbitrary multiple aquifer systems. The only requirement is that the sum of the β_{ij} values with respect to the overlying and underlying aquitards be of order 1 or less.

In summary, note once again the following features of the ratio method.

1. The method applies to arbitrary, leaky multiple aquifer situations.
2. The pumped aquifer can be either confined or unconfined.
3. The confining layers can be heterogeneous and anisotropic. Then the ratio method gives the average vertical permeability over the thickness z of the aquitard being tested.
4. The method relies only on early drawdown data, and therefore the pumping test can be of relatively short duration.
5. The drawdown data in the unpumped aquifer or in the aquitard provide an in situ indication of the time limit at which the ratio method ceases to give reliable results.
6. Since the method is more sensitive to time lag than to the actual magnitude of s'/s, the accuracy with which drawdowns are measured in the aquitard is not overly critical.
7. The method does not require prior knowledge of the aquitard thickness.
8. The ratio method is simple to use and does not involve any graphical curve-matching procedures. This lack of curve-matching procedures is an advantage because curve matching is often prone to errors due to individual judgment and because a more reliable result can be obtained by taking the arithmetic average of results from several values of the ratio s'/s.

METHOD FOR EVALUATING AQUIFERS

When the pumped aquifer is slightly leaky, one can evaluate its transmissibility and storage coefficient by the usual procedures based on the Theis equation. When leakage is appreciable, these procedures will not always yield satisfactory results. Alternative methods for analyzing the results of pumping tests in leaky aquifers were proposed by *Jacob* [1946] and *Hantush* [1956, 1960]. Still another method based on the r/B solution has recently been proposed by *Narasimhan* [1968]. All these methods rely on drawdown data from the pumped aquifer alone.

Their purpose is to determine not only the properties of the aquifer but also the so-called 'leakage factors' r/B and β that depend on the characteristics of the confining layers as well as on those of the aquifer. We have shown earlier that these methods have a limited application and that they can often lead to erroneous results.

Since we have introduced the ratio method as a means for evaluating aquitards, the only remaining unknowns to be determined are the aquifer transmissibility T and the storage coefficient S. When the aquifer is leaky, the use of methods based on the Theis solution will lead to errors whose magnitudes are a function of β and r/B. A look at *Neuman and Witherspoon* [1969*a*] will reveal that the smaller the values of β and r/B are, the less the drawdowns in the pumped aquifer deviate from the Theis solution, and therefore the smaller the errors introduced by such methods are. At this point we must recognize that β and r/B do not necessarily reflect the amount of water that leaks into the aquifer. In fact, both these parameters are directly proportional to r, which simply means that their magnitude in a given aquifer varies from nearly 0 at the pumping well to relatively large values further away from this well. Thus the extent to which leakage can affect the behavior of the drawdown in any given aquifer is a function of the radial distance from the pumping well. Thus the closer one is to this well, the smaller the deviations of drawdown from the Theis curve are. On the other hand, the rate of leakage is obviously greatest near the pumping well where the vertical gradients in the aquitard are largest and diminishes as the radial distance from this well increases. Therefore, in a given system, β and r/B increase with radial distance, whereas the actual rate of leakage decreases.

At first glance, we seem to be faced with a paradox: The greater the leakage is, the less the deviations from the nonleaky Theis solution are. However, a closer examination of the flow system will show that there is a simple physical explanation for this phenomenon. The reader will recognize that, although vertical gradients in the aquitard do not vary appreciably with radial distance from the pumping well, the same cannot be said about drawdown in a pumped aquifer. As a result the rate of leakage per unit area relative to this drawdown is negligibly small in the immediate vicinity of the pumping well but becomes increasingly important at larger values of r. In addition, the water that leaks into the aquifer at smaller values of r tends to act as a buffer to the pressure transient. This transient cannot propagate as fast as it otherwise might have had there been no increase in aquifer storage. The effect is to reduce further the drawdown at points farther away from the pumping well. The net result is a situation in which larger values of r are associated with less leakage but also with greater deviations from the Theis curve.

Thus we arrive at the important conclusion that one can evaluate the transmissibility and storage coefficient of a leaky aquifer by using conventional methods of analysis based on the Theis solution. The errors introduced by these methods will be small if the data are collected close to the pumping well, but they may become significant when the observation well is placed too far away. Therefore a distance drawdown analysis based on the Theis curve is not generally applicable to leaky aquifers and should be avoided whenever possible.

Ideally, the values of T and S should be evaluated by using drawdown or buildup data from the pumping well itself because here the effect of leakage is always the smallest. We recommend this approach whenever the effective radius of the pumping well is known (e.g., wells in hard rock formations). However, when a well derives its water from unconsolidated materials, its effective radius usually remains unknown owing to the presence of a gravel pack. In these situations the approach above can still be used to evaluate T but cannot be used to determine S.

As a general rule, early drawdown data are affected by leakage to a lesser degree than data taken at a later time are. Therefore we feel that in performing the analysis most of the weight should be given to the earliest data available, if, of course, there is confidence in their reliability.

Once S and T have been determined, one can calculate the dimensionless time at any given radial distance from the pumping well by

$$t_D = Tt/Sr^2 \tag{8}$$

Equation 8 can then be used with the ratio method as we discussed earlier.

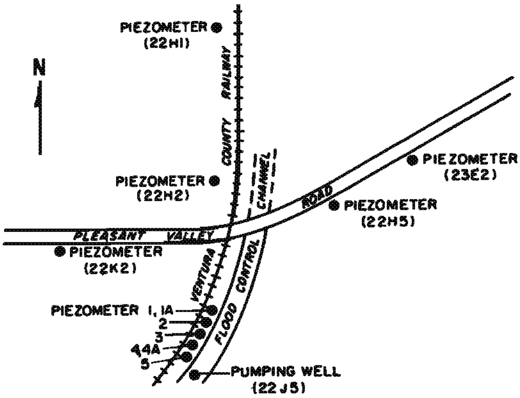

Fig. 4. The locations of the piezometers used in field pumping tests.

FIELD PUMPING TESTS IN THE OXNARD, CALIFORNIA, BASIN

The California Department of Water Resources had previously investigated the Oxnard basin in connection with seawater intrusion problems and constructed several wells at various locations in the basin. For our field studies we selected a particular location in the city of Oxnard where a large capacity pumping well (Figure 4, 22J5) was available to produce water from the Oxnard aquifer. Four additional piezometers (22H2, 22H5, 22K2, and 23E2) were available to monitor water levels in the Oxnard aquifer at radial distances of 502–1060 feet.

In addition, seven new piezometers were installed at various elevations relative to that of the Oxnard aquifer. Table 1 summarizes the vertical distances above or below the Oxnard for each piezometer and also gives the radial distances from pumping well 22J5. Ideally, the seven piezometers should have been arranged along a circular arc with its center at the pumping well so that responses would be given at various elevations but at only one unique value of r. However, this arrangement was not possible under the local conditions, and we therefore had to design the well field according to the scheme shown in Figure 4. For details of the construction, the completion, and the development methods, the reader is referred to *California Department of Water Resources* [1971, pp. 63–68].

The following is a brief description of the lithology in the vicinity of the test area. The semiperched zone is composed of fine- to medium-grained sand with interbedded silty clay lenses. The upper aquitard is made up of predominantly silty and sandy clays, mainly montmorillonite. The Oxnard aquifer, which is the most important water producer in the Oxnard basin, is composed of fine- to coarse-grained sand and gravel. Silty clay with some interbedded sandy clay lenses makes up the lower aquitard. The material that forms the Mugu aquifer is fine- to coarse-grained sand and gravel with some interbedded silty clay. Figure 5 shows an electric log through this series of sediments.

ANALYSIS OF PUMPING TEST RESULTS

Two pumping tests were performed in the field. Their purpose was to determine the hydraulic characteristics of the Oxnard aquifer and the confining layers above and below it and to confirm our theoretical concepts [*Neuman and Witherspoon*, 1969a] regarding the response of multiple aquifer systems to pumping.

The first pumping test lasted 31 days. Figure 6 shows the response in the Oxnard aquifer at

TABLE 1. Location of Piezometers

Piezometer	Distance from 22J5, feet	Depth, feet	Vertical Distance*, feet	Layer
1	100	120	···	Oxnard aquifer
1A	100	239	···	Mugu aquifer
2	91	225	−26	lower aquitard
3	81	205	−6	lower aquitard
4	72	95	+11	upper aquitard
4A	72	58.5	+50	semiperched aquifer
5	62	84	+22	upper aquitard

* The vertical distance is the distance above the top of the Oxnard aquifer at a depth of 105 feet or below the bottom at a depth of 198 feet.
† Failed to operate satisfactorily.

various radial distances from the pumping well. Piezometer 1, which is nearest to the pumping well, demonstrated an anomalous behavior during the first 6 min of pumping. This was apparently due to a surging effect in the pumping well. At about 6000 min the entire basin started experiencing a general drop in water levels probably due to the beginning of intermittent pumping for irrigation at this time of the year. Table 2 gives the values of T and S as calculated from these data by using *Jacob*'s [1950] semilogarithmic approach.

Table 2 shows that in general the values of T become progressively larger as r increases. This relationship can be explained as follows. Since the Oxnard aquifer is obviously leaky, the actual drawdown curve at any given well will lie below the Theis solution, as is shown diagrammatically in Figure 7. To demonstrate this positioning, we shall choose a particular point on the data curve that corresponds to some given value of s and t. If we could match the data to the true type curve where β and r/B are not 0, we would obtain the true value of s_{D_1} for the point chosen.

However, such type curves were not available for this investigation, and we used a method that is essentially equivalent to matching the field data to the Theis curve. Therefore the field data are being shifted upward from their true position, and our chosen point will now indicate an apparent value of $s_{D_2} > s_{D_1}$.

From the definition of s_D it is clear that since s remains unchanged the value of T is increased. The greater the radial distance r, the larger β and r/B become, and therefore the larger the difference between the true type curve and the Theis curve is. In other words, as r increases, the magnitude of T should become more and more exaggerated, which is clearly evident in Table 2.

With regard to errors in S, the shifting of field data as indicated on Figure 7 may be either to the left or to the right. Thus the effect on the calculated values of S is not predictable (Table 2). With this unpredictability in mind, we decided to select the results from piezometer 1 of $T = 130{,}600$ gpd/ft and $S = 1.12 \times 10^{-4}$ as being most representative of the Oxnard aquifer, at least in the area of the pumping test.

Having estimated the properties of the pumped aquifer, we shall now consider the results from other parts of this three-aquifer subsystem. Figure 8 shows the response at one particular point in the lower aquitard (well 3) as well as the responses in the Oxnard above (well 1) and the Mugu below (well 1A). Figure 9 shows the response at two different elevations in the upper aquitard (wells 4 and 5) as well as the response in the overlying semiperched aquifer (well 4A). Since piezometer 1 is located farthest from the pumping well, we do not have the response in the pumped aquifer directly below the piezometers where drawdowns in the upper aquitard were measured. However, from distance–drawdown curves in the Oxnard aquifer and from the behavior of piezometer 4, we concluded that the aquifer response was approximately as shown by the dashed curve in Figure 9. Remember that the ratio method for evaluating aquitards is more sensitive to the time lag than to the actual magnitude of drawdown in the aquifer. Therefore the dashed curve in Figure 9 can be considered sufficiently accurate for our purposes. Note that the shapes of the curves in Figures 8 and 9 are quite similar to those of our theoretical curves [*Neuman and Witherspoon*, 1969*a*].

To evaluate the lower aquitard, we shall determine the ratio s'/s at two early values of

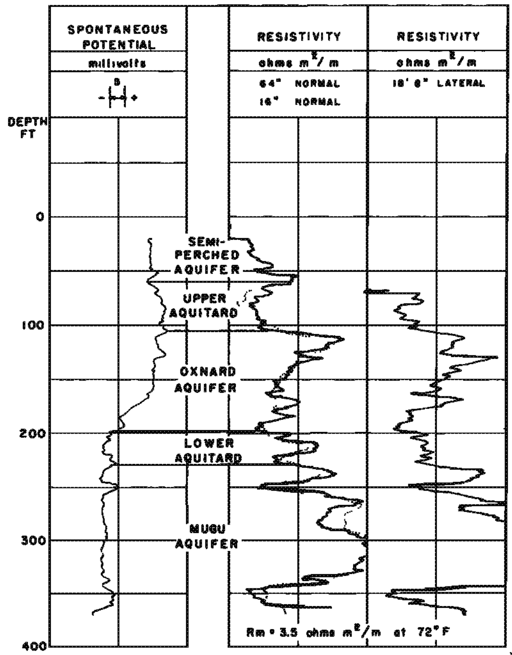

Fig. 5. The electric log from the first exploratory hole.

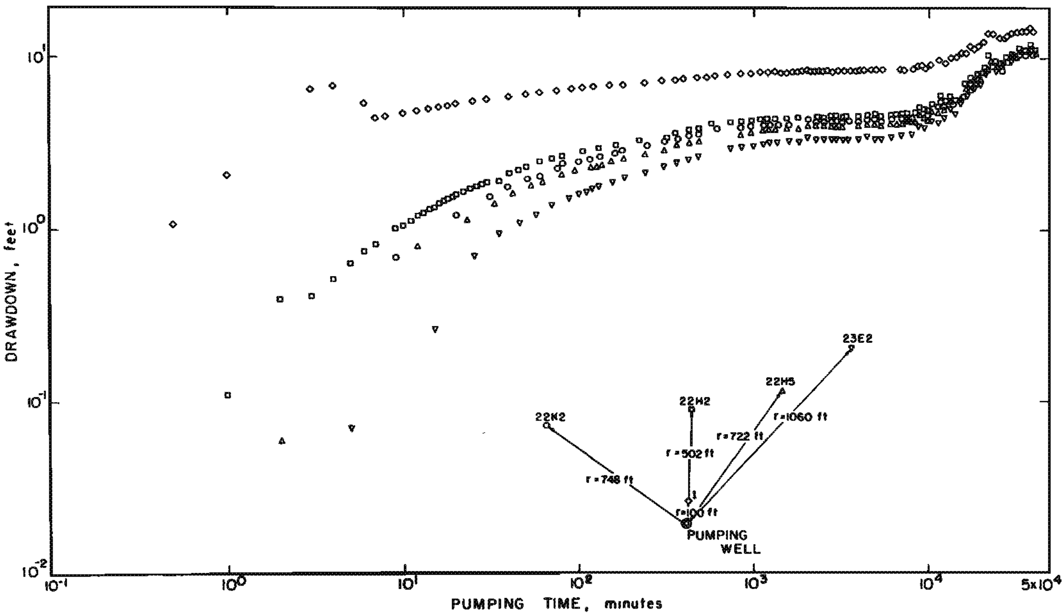

Fig. 6. The fluid levels in the Oxnard piezometers during the first pumping test. The diamonds represent well 1, the squares represent well 22H2, the triangles represent well 22H5, the circles represent well 22K2, and the inverted triangles represent well 23E2.

time, $t = 80$ min and $t = 200$ min. At $t = 80$ min, one can read on Figure 8 that $s' = 0.078$ and $s = 6.6$ feet. The ratio is simply $s'/s = 0.078/6.6 = 1.18 \times 10^{-2}$. To obtain t_D, one can use the equation

$$t_D = 9.28 \times 10^{-5} Tt/r^2S \qquad (9)$$

where T is in gallons per day per foot, t is in minutes, and r is in feet. Then, using the known values of T and S and noting from Table 1 that, at piezometer 3, $r = 81$ feet, one can calculate

$$t_D = \frac{(9.28 \times 10^{-5})(130{,}600)(80)}{(81)^2(1.12 \times 10^{-4})} = 1.32 \times 10^3$$

TABLE 2. Results of Oxnard Aquifer Using Jacob's Semilog Method

Well	r, feet	T, gpd/ft	S
1	100	130,600	1.12×10^{-4}
22H2	502	139,000	3.22×10^{-4}
22H5	722	142,600	3.08×10^{-4}
22K2	748	136,700	2.48×10^{-4}
23E2	1060	157,000	2.53×10^{-4}

Referring to Figure 3, one finds that these values of s'/s and t_D correspond to $t_D' = 0.086$. From the definition of t_D', one can verify the formula

$$\alpha' = 1.077 \times 10^4 t_D' z^2/t \qquad (10)$$

where α' is in gallons per day per foot, z is in feet, and t is in minutes. One notes from Table 1 that, for piezometer 3, $z = 6$ feet, and therefore

$$\alpha' = \frac{(1.077 \times 10^4)(0.086)(6)^2}{(80)} = 4.17 \times 10^2 \text{ gpd/ft}$$

Similarly, one finds that, at $t = 200$ min, $\alpha' = 3.39 \times 10^2$ gpd/ft. Since the method gives more reliable results when t is small, we adopted $\alpha' = 4.17 \times 10^2$ gpd/ft as the representative value for the top 6 feet of the lower aquitard. The results of similar calculations for both aquitards are summarized in Table 3. Note that the diffusivity of the Oxnard aquifer is

$$\alpha = \frac{T}{S} = \frac{130{,}600}{1.12 \times 10^{-4}} = 1.17 \times 10^9 \text{ gpd/ft}$$

which is more than 1 million times the values obtained for the aquitards.

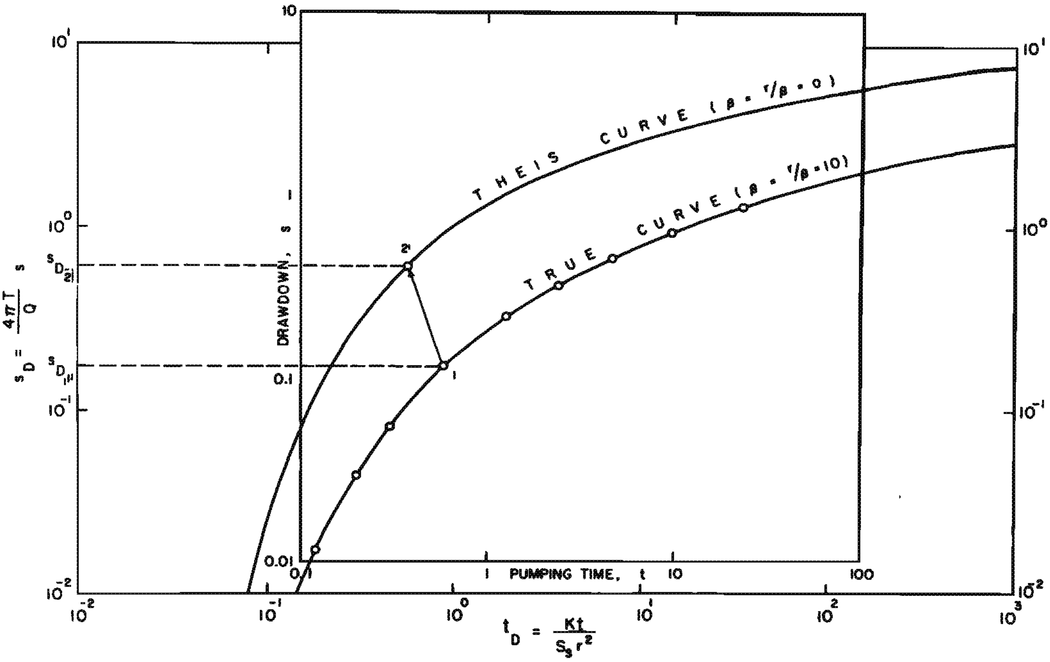

Fig. 7. A comparison of hypothetical field data with leaky and nonleaky type curves.

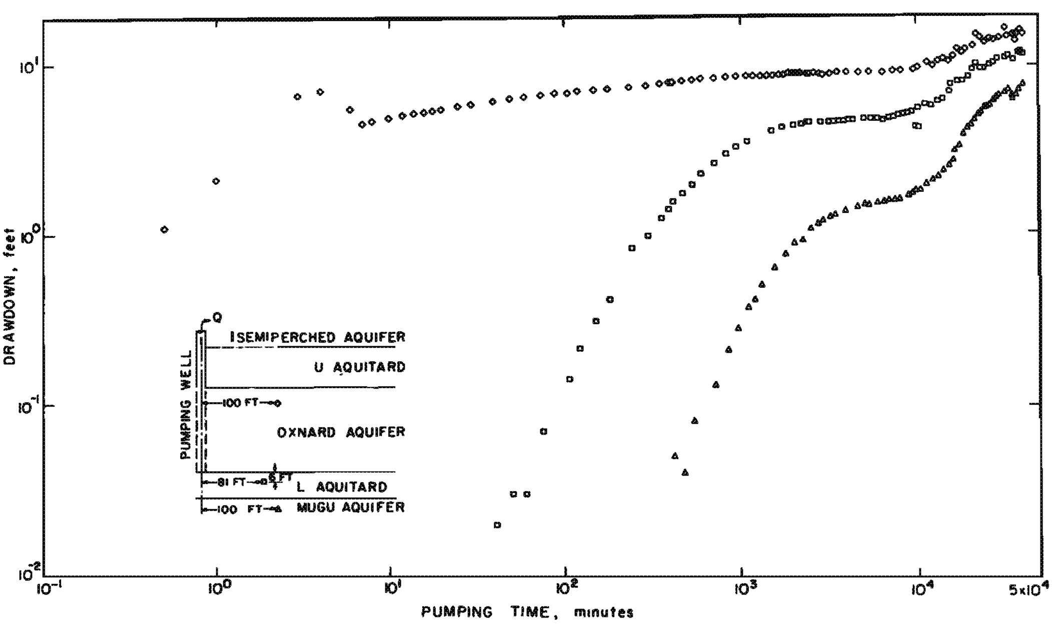

Fig. 8. The response of the piezometers in the lower aquitard (well 3, squares) to that in the Oxnard (well 1, diamonds) and Mugu (well 1A, triangles) aquifers during the first pumping test.

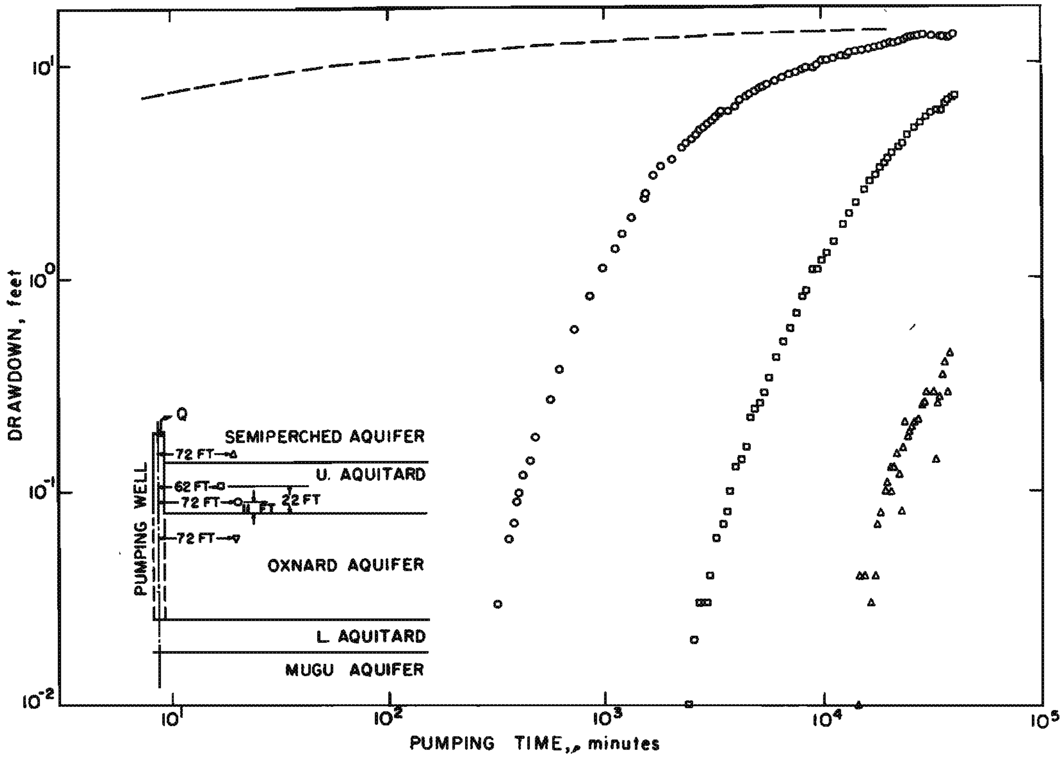

Fig. 9. The response of the piezometers in the upper aquitard (well 4, circles, and well 5, squares) and the semiperched aquifer (well 4A, triangles) during the first pumping test. The broken line indicates the probable response of the Oxnard aquifer at $r = 72$ feet.

The results of the second pumping test were essentially the same as those of the first test and will therefore not be presented here.

DETERMINATION OF AQUITARD PROPERTIES USING FIELD AND LABORATORY RESULTS

Having determined the hydraulic diffusivities, we can evaluate the permeability K' of each aquitard if the storage factor is known. The values of S_s' were calculated from consolidation tests performed in the laboratory [*California Department of Water Resources*, 1971, pp. 106–110] by using the formula

$$S_s' = a_v\gamma_w/(1 + e) \tag{11}$$

These values were then used to calculate K' according to

$$K' = \alpha' S_s' \tag{12}$$

and the results are summarized in Table 4.

TABLE 3. Results for Hydraulic Diffusivity of Aquitards from First Pumping Test

Layer	Section Tested	K'/S_s', gpd/ft	K'/S_s', cm²/sec
Upper aquitard	bottom 22 feet	1.02×10^2	1.47×10^{-1}
Upper aquitard	bottom 11 feet	2.44×10^2	3.51×10^{-1}
Lower aquitard	top 6 feet	4.17×10^2	5.99×10^{-1}

Direct measurements performed on undisturbed samples in the laboratory indicated that the aquitard permeabilities vary within a range of at least 3 orders of magnitude. The results in Table 4 fall on the high side of this range and thus are an indication that the average permeability in the field cannot always be reliably estimated from laboratory measurements.

It is interesting to compare the specific storage and permeability of the aquitard with those of the Oxnard aquifer. Using an aquifer thickness

TABLE 4. Hydraulic Properties of Aquitard Layers

Layer	Section Tested	Specific Storage S_s'		Permeability K'	
		cm^{-1}	ft^{-1}	cm/sec	gpd/ft^2
Upper aquitard	bottom 21 feet	7.88×10^{-6}	2.4×10^{-4}	1.11×10^{-6}	2.45×10^{-2}
Upper aquitard	bottom 11 feet	7.88×10^{-6}	2.4×10^{-4}	2.66×10^{-6}	5.85×10^{-2}
Lower aquitard	top 6 feet	3.28×10^{-6}	1.0×10^{-4}	1.89×10^{-6}	4.17×10^{-2}

of 93 feet, one has

$$K = \frac{T}{b} = \frac{130{,}600}{93} = 1405 \text{ gpd/ft}^2$$

and

$$S_s = \frac{S}{b} = \frac{1.12 \times 10^{-4}}{93} = 1.20 \times 10^{-6} \text{ ft}^{-1}$$

Thus the permeability of the aquifer exceeds that of the aquitards by more than 4 orders of magnitude. However, note that the specific storage of the aquifer is less than S_s' in the aquitards above and below by 2 orders of magnitude. In other words, for the same change in head a unit volume of aquitard material can contribute about 100 times more water from storage than a similar volume of the aquifer can. This statistic confirms our belief that storage in the aquitards must be considered when one deals with leaky aquifer systems.

NOTATION

- a_v, coefficient of compressibility, equal to $-\Delta e/\Delta p$, LT^2M^{-1};
- b_i, thickness of ith aquifer, L;
- b_j', thickness of jth aquitard, L;
- e, void ratio;
- K_i, permeability of ith aquifer, LT^{-1};
- K_j', permeability of jth aquitard, LT^{-1};
- p, pressure, $ML^{-1}T^{-2}$;
- Q_i, pumping rate from ith aquifer, L^3T^{-1};
- r, radial distance from pumping well, L;
- r/B_{ij}, dimensionless leakage parameter, equal to $r(K_j'/K_ib_ib_j')^{1/2}$;
- s_D, dimensionless drawdown, equal to $4\pi T_is/Q_i$;
- s_i, drawdown in ith aquifer, L;
- s_j', drawdown in jth aquitard, L;
- S_i, storage coefficient of ith aquifer, equal to $S_{si}b_i$;
- S_{si}, specific storage of ith aquifer, L^{-1};
- S_{sj}', specific storage of jth aquitard, L^{-1};
- t, pumping time, T;
- t_{Di}, dimensionless time for pumped ith aquifer, equal to $K_it/S_{si}r^2$;
- t_{Dj}', dimensionless time for jth aquitard, equal to $K_j't/S_{sj}'z^2$;
- T_i, transmissibility of ith aquifer, equal to K_ib_i, L^2T^{-1};
- z, vertical coordinate, L;
- α_i, hydraulic diffusivity of ith aquifer, equal to K_i/S_{si}, L^2T^{-1};
- α_j', hydraulic diffusivity of jth aquitard, equal to K_j'/S_{sj}', L^2T^{-1};
- β_{ij}, dimensionless leakage parameter, equal to $r/4b_i(K_j'S_{sj}'/K_iS_{si})^{1/2}$;
- γ_w, specific weight of water, $ML^{-2}T^{-2}$.

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Attachment C

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EDUCATION

Ph.D. in **Hydrology**, with minor in **Mathematics**, University of Arizona, 2006
MS in Mining, Geological and Geophysical Engineering, University of Arizona, 2001
BS (Honors, Cum Laude) in Mining Engineering, University of Arizona, 1999

APPOINTMENTS

09/2017-Present: **Associate Professor**
Department of Natural Resources & Environmental Management
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09/2014-2017: **Assistant Professor**
Department of Natural Resources & Environmental Management
California Polytechnic State University, San Luis Obispo, CA

08/2010-08/2014: **Senior Member of Technical Staff**
Sandia National Laboratories, Carlsbad, NM

08/2009-07/2010: **Assistant Professor**
Department of Geological Engineering, Montana Tech of the University of Montana

08/2008-08/2009: **Assistant Research Professor**
CGISS & Department of Geosciences, Boise State University

06/2006-07/2008: **Postdoctoral Research Scientist**
CGISS & Department of Geosciences, Boise State University

08/2003-08/2006: **Research Associate** (PhD Candidate)
Department of Hydrology and Water Resources, University of Arizona

08/1999-07/2003: **Research Assistant** (MS Candidate)
Department of Mining and Geological Engineering, University of Arizona

TEACHING EXPERIENCE

California Polytechnic State University, NRES Department
Environmental Soil Physics (SS 424, formerly SS 432)
Environmental Groundwater Hydrology (SS 442, formerly Vadose Zone & Groundwater Processes)
Environmental Contaminant Transport (ERSC 443)
Advanced Environmental Science (ESCI 550)
Physical Geology (GEOL 201)
Introduction to Earth Science (ERSC 144)
Introduction to Soil Science (SS 120, formerly SS 121)
Undergraduate Seminar (NR 363, formerly ERSC 363)

Geological Engineering, Montana Tech
Hydrogeology for engineers
Numerical methods for groundwater flow modeling
Advanced hydrogeology.

Geosciences, Boise State University
Applied Hydrogeology
Advanced Hydrogeology.

Pima Community College, Tucson, Arizona
College Algebra; Trigonometry; Statistics.

Mining and Geological Engineering, University of Arizona (Graduate instructor)
Underground Mine Ventilation.

SERVICE

GEGB, CAFES Representative
Graduate Coordinator, MS Ag Soil Science Specialization.
Search Committee, Soil Ecology Position.
Search Committee, Soil Fertility/Health Position.
Supervising Graduate Students.
Convener and Chair of several American Geophysical Union (AGU) oral and poster sessions.
Served as MS Committee Member Forestry Science Graduate.
Member AGU Groundwater Technical Committee.
Served on Graduate Committee at Montana Tech of the University of Montana.
Served on Multiple Masters Student Thesis committees.

GRANTS

ARI (Co-PI, 2020-2021) (**Funded**)
Cal Poly Strategic Research Initiatives (2020), $500,000 (Not funded)
Central Coast Salmon Enhancement (2020), $26,593 (**Funded**)
CDFA – Health Soils (Co-PI, 2018-2020), $206,771 (**Funded**)
NASA (2018), $50,317 (**Funded**)
California Department of Pesticide Regulation (2017), $500,000 (Not funded)
National Science Foundation (2017), $297,389 (Not funded)
California Department of Water Resources (2017), $35,801 (**Funded**)
California Department of Food and Agriculture – FREP (2017), $222,253 (Not Funded)
ARI Campus (2017), $75,000 (Not funded)
RSCA Grant (2017), $14,000 (**Funded**)
RSCA Grant (2016), $12,000 (**Funded**)
USDOE-UFD (2016), $800,000 (Not funded)
USDA-NIFA Exploratory Research (2016), $100,000 (Not funded)
CDFA-FREP (2016), $100,000 (Not funded)
ARI Seed Grant (2015), $5000 (**Funded**)
ARI New Investigator (2015), $39,663 (**Funded**)
McIntire-Stennis (2015), $29,927 (**Funded**)
USDOE-UFD (2015), $800,000 (Not funded)

Montana Water Center (2010) $13,000 (Funded)
New Mexico Small Business Administration (2013) $17,000 (Funded)

PRIVATE CONSULTING PROJECTS (Founder ***AquiFAnalytics, LLC*** 2014)
Sandia National Laboratories, Carlsbad, NM (2014-2017), $50,000
Sandia National Laboratories, Albuquerque, NM (2019), $8140
Cleath-Harris Geologists, San Luis Obispo, CA (2015-2017), $5000

PUBLICATIONS

1. Heath, J.E., Kuhlman, K.L., Broome, S.T., Wilson, J.E., **Malama, B**. (2021) *Heterogeneous Multiphase Flow Properties of Volcanic Rocks and Implications for Noble Gas Transport from Underground Nuclear Explosions*, Vadose Zone Journal (Accepted)
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SELECTED ABSTRACTS

1. **Malama, B.,** Iason E. Pitsillides (2020, submitted) *Deep Sensing of Transient Electrokinetic Response of Aquifer-Aquitard System to Pumping*, AGU Fall Meeting, December, San Francisco, CA.

2. **Malama, B.,** Solum James (2019) *Two Years of Sap Flow for Evapotranspiration Characterization in Riparian Vegetation*, AGU Fall Meeting, December, San Francisco, CA.
3. **Malama, B.,** Jack T. Ridder, Nico Hillman, Shelby Littleton (2019*) Transient Electrokinetic Signals Measured above a Fractured Rock Aquifer,* AGU Fall Meeting, December, San Francisco, CA.
4. Kuhlman, K.L., **Malama, B.** (2019) *Eigenvalue Uncoupling of Electrokinetic Flows. AGUFM, 2019*, H21H-1815.
5. Pritchard-Peterson, D., **Malama, B.** (2017) *Field Investigation of Stream-Aquifer Interactions - A Case Study*, AGU Fall Meeting, December, New Orleans, LA.
6. Aurelius, S., Platt, D.C., **Malama, B.** (2017) *Characterization of California Central Coast Aquifers using Pneumatic Slug Tests*, AGU Fall Meeting, December, New Orleans, LA.
7. **Malama, B.** (2017, accepted) *The Stream Depletion Model Paradox - A First Solution*, AGU Fall Meeting, December, New Orleans, LA.
8. **Malama, B.,** Abere, M., Montgomery, M. (2016) *Characterizing Multi-layered Coastal Aquifer using Pneumatic Slug Tests*, AGU Fall Meeting, December, San Francisco, CA.
9. Mishra, P.K., Alves Silva, L.P., **Malama, B.** (2015) *Semi-analytical model for slug test in unconfined aquifers*, AGU Fall Meeting, December, San Francisco, CA.
10. **Malama, B.** (2014) *Transient Streaming Potentials under Varying Pore-water Ionic Strength*, AGU Fall Meeting, December, San Francisco, CA.
11. Kuhlman, K.L., **Malama, B.**, Heath, J.E., Gardner, W.P., Robinson, D.G. (2013) *Multi-porosity transport of natural tracers in a fractured system*, AGU Fall Meeting, San Francisco, CA.
12. **Malama, B. (2013)** *Transient streaming potentials associated with brine flow in rock salt*, AGU Fall Meeting, San Francisco, CA.
13. **Malama, B. (2013)** *Transient streaming potentials: a proxy for hydraulic head? Results from lab-scale pumping test simulations*, NGWA Ground Water Summit, San Antonio TX.
14. **Malama, B.** (2012) *Modeling transient streaming potentials in coupled saturated-unsaturated zone flow to a pumping well*, AGU Fall Meeting, San Francisco, CA.
15. **Malama, B.** (2012) *Estimation of the electrokinetic coupling coefficient and hydraulic conductivity from streaming potential measurements in a falling-head permeameter*, NGWA Ground Water Summit, Garden Grove, CA.
16. **Malama, B.** (2011) *Aquifer characterization using transient streaming potentials generated by flow during pumping tests - New developments*, AGU Fall Meeting, San Francisco, CA.
17. **Malama, B.** Lee, M. (2011) *Application of multirate mass transfer model to radionuclide transport in Culebra Dolomite core*, in Proceeding of the International Symposium on Radiation Safety Management, November 2-4, 2011, Gyeongju, Republic of Korea.
18. **Malama, B.** (2010) *Hydraulic characterization of the shallow subsurface in the Butte--Silver Bow area in southwestern Montana, using pneumatic slug tests*, AGU Fall Meeting, San Francisco, CA.
19. **Malama, B.** Kuhlman, K.L., Revil, A., (2009) *Modeling aquifers using transient streaming potentials*, submitted to AGU Fall Meeting, San Francisco, CA.

20. Thoma, M., **Malama, B.**, Barrash, W., Bohling, G., Butler Jr., J.J. (2009) *A general model for using slug tests in unconfined aquifers: Assessment of skin effects*, AGU Fall Meeting, San Francisco, CA.
21. **Malama, B.**, Revil, A., Kuhlman, K. L., (2008) *A semi-analytical solution for transient streaming potentials associated with confined aquifer pumping tests*, AGU Fall Meeting, San Francisco, CA.
22. Thoma, M., **Malama, B.**, Bradford, J., Barrash, W., Johnson, B., Hinz, E., Murray, S. (2008) *Using Ground Penetrating Radar to Monitor Transient Unconfined Aquifer Response to Pumping*, AGU Fall Meeting, San Francisco, CA.
23. **Malama, B.**, Kuhlman, K. L., Barrash, W. (2007) *Leakage theory for unconfined aquifers*, AGU Joint Assembly, Acapulco, Mexico.
24. **Malama, B.**, Barrash, W. (2006) *Solute Transport in a Medium with Spatially Variable Porosity*, AGU Fall Meeting, San Francisco, CA.
25. **Malama, B.** Neuman, S.P. (2004) *Inverse stochastic moment analysis of transient flow in randomly heterogeneous media*, AGU Fall meeting, San Francisco, CA.
26. **Malama, B.**, Kulatilake, P.H.S.W., Park, J. (2003) *A New Rock Mass Strength Criterion for Biaxial Loading Conditions*, 39th US Rock Mechanics Symposium, MIT.

MANUSCRIPTS IN PREPARATION

1. James Solum, Bwalya **Malama**, *Estimating Riparian Forest Evapotranspiration by Upscaling Single-Plot Sap Flow Measurements.*
2. **Malama, B.,** Iason Pitsillides, Braden Povah, *Transient Electrokinetic Response of a Shallow Aquifer-Aquitard System to Groundwater Pumping.*
3. **Malama, B.**, Whetsler, B, *Finite Element Modeling of a Coastal California Aquifer.*

COMPUTATIONAL SKILLS

Numerical Methods: Finite element and Finite difference methods.
Programming: C++, MATLAB, Python, FORTRAN.
Modeling: COMSOL Multiphysics, MODFLOW, TOUGH, AQTESOLV.

PROFESSIONAL MEMBERSHIPS

American Geophysical Union (AGU)
National Ground Water Association (NGWA)
Groundwater Resources Association of California (GRAC).